Response to Referees' Comments

We are grateful for the referees in pointing out where more information should be provided and where clarification is needed. In the responses below, we include additional information to bolster claims made in the manuscript. We disagree with the referees on a number of points, as indicated.

These responses are provided in the order in which the referees' comments were made. These responses are provided in the order in which the referees' comments were made. The referee comments are italicized.

Referee No. 2

1) *To circumvent this problem* (of very large grain size), *the authors analyzed composite sections constructed from serial sectioning of blocks 15x15x30 cm blocks. The technique is presented as new, but use of multiple coherently-oriented samples to analyze a representative volume of coarse-grained materials is a rather traditional (and effective) solution for this problem.*

We do <u>not</u> claim that using multiple coherently-oriented sections to obtain a sufficiently large sample size for coarse-grained ice is new, our method of doing this is new, which makes it practical for EBSD work. See response #2 to the first referee.

2*) Given the fact that the authors still observe multiple maxima CPO patterns for all analyzed composites, one may question if the technique proposed is really effective (the spacing used for the sectioning is probably still smaller than the maximum dimension of the grains). One may therefore question why should one prefer this method to the even more traditional one (at least in geology) of collecting oriented samples in a series of profiles normal to the shear zone trend and then add up the data for samples with similar positions across the shear zone. This second approach would allow to: (1) spread the sampling a much larger volume, (2) preserve the relation between CPO and microstructure, which is essential for discussing the role of deformation and recrystallization processes on the evolution of the CPO, and (3) collect data for variable finite strains (which is missing here and would have been extremely useful to discuss some features, such as the deviation of the [0001] maxima relatively to the normal to the shear plane along the plane normal to the shear direction or how the CPO evolves with finite strain).*

Doing what the referee proposes would be impractical for the situation encountered in this and most valley glaciers. We do not have clear markers of shear strain that allow us to document a strain gradient across the marginal ice, but we can reasonably assume that fairly closely spaced samples come from a homogeneously deformed volume of ice. Collecting, handling, transporting and preparing for analysis many more large samples was beyond the resources available to us. We could not do on a large scale what Hudleston (1977) was able to do on the scale of a single thin section (and what the referee suggests here) for a small-scale shear zone in cold ice at the margin of the Barnes Ice Cap. However, more systematic sampling, allowing for individual slices of each composite to be spaced by >15cm would be beneficial and appropriate for a follow-up study.

3) *In conclusion, neither the results nor the technique are completely new. If the article is to be published (I do not know the journal well enough to make a recommendation), it has to be revised to present in a more objective way its actual contribution: new data on the evolution of CPO of ice in natural shear zones, which confirm the current knowledge on the subject: simple shear under high homologous temperature produces a CPO characterized by concentration of [0001] axes normal to the shear plane.*

We refer to the response #1 of the first referee to emphasize what is new in our study. We should note that all natural ice deformation is under conditions of high homologous temperatures. There is almost no new data for the evolution of CPO of natural ice in shear zones, because there is very little close control of strain gradients in natural ice. Nearly all the published data comes from laboratory experiments. As far as we are aware there is still only one study of fabrics in natural ice constrained to be from a well-defined shear zone (Hudleston, 1977).

4) *Moreover, the discussion should be reinforced and present a comparison of the observations with all available experimental data in simple shear (why focus the comparison on a single set of experiments?)*

As far as we are aware there are only two published sets of experiments that document both c-axis and a-axis fabrics in simple shear in ice, and those are the ones by Qi et al. (2019) and Journaux et al. (2019), both of which we cite and the results of which we compare with our data. In the case of Qi et al. (2019), we show how taking a subset of the data leads to less well defined fabric patterns that might be compared to natural fabric patterns with limited grain counts. We do cite other experiments done in simple shear or in simple shear plus compression normal to the shear plane, but the data in these is not presented in way that allows for direct comparison with our data or the data of Qi et al. (2019).

5) *The rather 'surprising' observations of: (1) lack of a maximum of <a>-axes parallel to the flow direction and (2) the deviation of the [0001] maxima relatively to the normal to the shear plane along the plane normal to the shear direction - should be discussed in a more effective way. The present discussion, although long, does not propose any clear explanation for neither of the two observations.*

We do not have a good explanation for the first point here, and the switch with increasing strain from a-axes perpendicular to flow at low strain to parallel to flow at high strain was not explained by Qi et al. (2019) or Journaux et al. (2019) in their experiments. The second point we do discuss (l. 379-385) though perhaps could do so more effectively. The deviation or spreading of the main [0001] maximum in a plane normal to the shear plane and in a direction perpendicular to the shear direction (see response #1, fig. R2) is found both in simple shear experiments (Kamb, 1972; Bouchez and Duval, 1982; Journaux et al., 2019) and in experiments involving simple shear with the added effect of compression or flattening normal to the flow plane (Kamb, 1972; Budd et al., 2013; Li et al., 2000). The combination of uniaxial compression (cone distribution about the compression axis) with simple shear (single maximum perpendicular to the shear plane for large strains) provides the clearest explanation for the split maximum (Kamb, 1972; Budd et al., 2013). Bouchez and Duval (1982), and Journaux et al. (2019), however, observe the tendency for the main c-axis maximum to spread in experiments using fixed plattens where compression could not be a factor. Li et al. (2000) attribute the spreading to transverse extension accompanying the flattening of the sample during deformation in their experiments. Numerical simulations by Llorens et al. (2016a, 2017) show this spreading does occur in simple shear with no flattening strain, and that it is enhanced by dynamic recrystallization. It is most pronounced at low strain rates. Qi et al. (2019) suggest that the spreading increases with increasing shear strain. In our case, at the margins of Storglaciären, the ice is deforming at high temperatures, low strain rates, and to high strain, consistent with conditions that enhance spreading in experiments and in modeling.

6) *The statements presenting the relation between microphysical processes and CPO evolution in the abstract, introduction, discussion, and conclusion lack precision and give the (false, in my point of view) impression that CPO evolution is mainly controlled by recrystallization (cf. lines 15 & 58-60) or that dynamic recrystallization may completely reset the CPO (cf. lines 30-32 & 434-436). As I see CPO is produced by dislocation glide and recrystallization modifies it, by creating new orientations (most often only dispersion around the orientation of the parent grains) and selectively consuming others when grain growth is effective as it is the case here. The first process certainly buffers the increase in the CPO intensity, but not fully resets the CPO. The second may significantly change the CPO when grain growth is orientation dependent*

We agree entirely with how the referee interprets the CPO and thought that is what we stated in the manuscript. We apparently have given a false impression. We will attempt to clarify.

7) *Which are the arguments which justify that low strain rates should enhance dynamic recrystallization and grain growth (l. 434)? I would rather propose the opposite as the forces associated with dislocation density gradients should be smaller at low strain rates.*

See the response to point #14 of the first referee.

8) *Referencing is often loose and there are many places where pertinent references are missing. For instance, l. 61, Wenk and Christie (1991) is not the best reference in a phrase dealing with CPO-induced mechanical anisotropy when there are a large number of studies that investigated precisely this effect (cf. review by Gagliardini et al. 2009 and references therein).*

This is a fair point, which can be addressed, although we believe that Wenk and Christie (1991) is an important reference as these authors discuss the effect of CPO on the internal flow strength of rocks (relating back to the many important purposes for studying ice l. 42-45). Examples of additional references, relating specifically to CPO development modifying the internal flow strength of polycrystalline ice include: Steinemann, 1958; Lile, 1978; Pimienta and Duval, 1987; Alley, 1988; Alley, 1992; Azuma and Azuma, 1996; Gagliardini, 2009.

9) *The aims of the article should also be redefined. Those stated in l.79-82 were probably the initial aims of the study, but given the results, they cannot be the aims of the article.*

We are puzzled by this comment. The aims of the study are as given in lines 79-82. The only thing we might change is to replace the word "fully" by "better," since we have not fully addressed the issue of sampling in coarse-grained ice.

10) *The authors indicate that 8 areas were sampled and that at least two composite sections were made for each of the eight samples. However, in the map only 4 sampling sites are located and data is shown for only 3 samples. Why? Where are the data for SG6-B, which seems from its location in the map to sample a lower strain domain?*

Data for SG6-B are presented in figure 2. This sample was collected and analyzed prior to developing the sample preparation method for EBSD. In order to measure enough grains from the block SG6-B, the entire sample was used to create enough thin sections (7) to measure ~100 grains. Therefore we could not re-analyze it using EBSD. We present the compilation of c-axis measurements from the seven thin sections of this sample, done using a U-stage, to illustrate a particular point. While SG6-B might be from a slightly lower strain domain, there is little control of strain gradients in natural ice (see comment #3), and this sample was collected in the same intensely sheared marginal ice as SG23, SG27 and SG28. We do not expect its fabric to differ significantly from the fabrics in these. This will be clarified in the revision.

The samples we collected in the 2018 field season were concentrated along the margins and at the front of the ablation zone l. 204-205. We focused on SG23, SG27 and SG28 for the purposes of this paper because as noted, we collected more samples than the four for which we present data in this paper. These four are from a small area with well defined kinematics in the highly sheared marginal ice. The others were spread out across the glacier in various and more complex local settings, were not clustered in such a way that data could be combined to produce a CPO with a sufficient number of grains for a strong interpretation, and thus do not contribute to the arguments we present here.

11*) In l. 294, it is indicated that EBSD work is performed on 40mm x 60mm sections. However, all EBSD maps presented in the article are much smaller (25 x 25 mm on average in Fig. 6a and 3.5 x <3 mm in Fig. 7a). Why use a reduced analysis area in a study where the size of the mapped area is critical?*

The reviewer brings up a good question. The copper and aluminum ingots on which the samples were mounted were up to 40 x 60mm because that is the maximum size the SEM can analyze without significant risk of sample crashes (Prior et al 2015 show a larger sample but 40x60 is now the standard max size). This size pushes the limits of the instrument, and therefore we aimed to make sections that were not quite 60mm wide. We experimented with the width of the composite slices, initially starting with 5mm (see Fig. 7, SG23 composite 2 EBSD image—this was the first composite constructed), which did not provide many grains. We determined that for bulk CPO analysis, in order to maximize the number of grains, we needed to use more slices that were thinner. We ultimately aimed for 36 spaced slices per sample - 18 per composite - that were each approximately 2mm wide. This allowed for some extra room, which was important because different bubble concentrations throughout the sample made certain areas more fragile than others. Slices in areas with a high bubble concentration needed to be a bit wider. Ultimately, most of the composite sections were between 36 and 50mm wide. Thus it was practical considerations that limited the width of the sections we produced. This will be clarified in the revision.

For whole sections, we were interested in examining the internal structure of the largest grains, which included subgrain boundaries, and also the misorientations between grain boundaries. Many of the sections measured were mounted on the larger ingots (40 x 60 mm), but due to the limited number of these, some were mounted on smaller ingots (30 x 30 mm). All produced similar analytical results. We chose to show sections from the smaller ingots (Fig. 6a,b) because the data resolution was high (not many mis-indexed points/holes in the data, or cracks in the section) in comparison with those from the larger ingots. These sections highlight all the features we discuss.

References:

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